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14. ABSTRACT
Receiver coil arrays to improve the sensitivity of magnetic resonance for use in materials detection applications are considered. In particular, cooled coils, coils for producing circularly polarized magnetic RF fields, coil arrays for multiple frequency magnetic resonance excitation and detection, and coils which are not physically closed are considered.

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Magnetic Resonance, NQR, Explosive Detection, Materials Detection

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Year End and Final Report

Grant No. N00173-98-1-G015
"Study of Magnetic Resonance Sensitivity for Detection of Materials:
Are Multiple Coil Arrays Better than Single Coils?"
July 1999 - December 2000
B. H. Suits, Michigan Technological University, Houghton, MI 49931

This is the year end report for the second and final year of the grant "Study of Magnetic Resonance Sensitivity for Detection of Materials: Are Multiple Coil Arrays Better than Single Coils?" grant No. N00173-98-1-G015. In response to a delay in funding for the second year, the end date of the grant was extended to 31 Dec 2000 and this report covers the period from July 1999 to that end date.

One of the principle conclusions made during the first year of this grant was that a simple array of coils used only as a means to improve the signal to noise ratio (SNR) was not likely to succeed. During the second year, other considerations and other types of arrays were considered and several promising uses for coil arrays were discovered. During the course of these studies, results have been communicated to Garroway's group at NRL as they become available. Many of the results below benefitted from ongoing discussions with that group as well. A summary of these investigations, roughly in chronological order, follows. Also attached is a list of invention disclosures, publications, and presentations given which are related to this work.

Cooled Coils

The ^{14}N NQR signal is inherently weak which leads to difficulties when it is used as a technique to detect some materials – most notably TNT. Hence, a factor of two improvement in the signal-to-noise ratio (SNR) could make the difference between a viable detector and one which is only marginal. In fact, during the summer of 1999, L. Burnett of Quantum Magnetics suggested to this author that a factor of two improvement over the current state of the art would be very important for the detection of TNT samples the size of anti-personnel mines.

A quick estimate shows that cooling the RF (receive) coil to liquid nitrogen temperatures (77K) should yield a factor of two improvement in the SNR. There are two contributing factors: the coil quality factor goes up as the coil's resistance goes down at lower temperatures and the inherent thermal noise in the coil also decreases.

The quality factor of the coil depends on the coil geometry and the resistivity of the material which makes up the coil. For simple metals, such as copper, one can expect the resistivity to be proportional to temperature, and hence the RF resistance (which depends also on the skin depth for RF penetration) should decrease proportional to the square root of the (absolute) temperature. The thermal noise (voltage) in the coil will decrease as the square root of the temperature as well. The received signal depends on the square root of Q for a tuned and matched coil. Hence, designating room temperature (T_{RT} = 300K) as T_{RT} the SNR at another temperature should be

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given by

$$SNR_T = SNR_{RT}\left(\frac{T_{RT}}{T}\right)^{-1/2}$$

So cooling the coil to 77K should result in an increase in the SNR by a factor of 1.97.

To test this, a simple circular coil made from roofing copper (22 cm i.d., 26.5 cm o.d.) was constructed along with a simple syrofoam container for the coil which would allow the introduction of liquid nitrogen. The coil was tuned to 3.5 MHz using high-Q ATC capacitors. Upon cooling the unloaded, unmatched Q of the coil measured using the 2-probe technique increased from 480 to 1200, a factor of 2.5 , a bit larger than predicted. The slightly larger factor is likely due to a change in the current distribution within the coil, which is neglected in the simple estimate above. If the noise remains constant, this change in Q should yield a change in SNR of 1.58.

The actual received noise depends on the thermal noise from the tuned probe plus the noise added during amplification of the signal. A good RF amplifier used for magnetic resonance near 3 MHz will have a noise figure of 1 dB. This corresponds to a noise temperature of about 77K. The amplifier noise figure is calculated (or measured) assuming the probe has an appropriate impedance (e.g. 50 Ω) and is at room temperature. The noise contribution from the amplifier does not change as the coil temperature is lowered, and hence will always be about 77K/300K ≈ 1/4th that of the room temperature probe. Hence, designating the noise power at 77K as "one unit of noise," the probe plus amplifier will have a total of 5 units of noise at room temperature and 2 units at 77K. Hence the noise power is reduced by a factor of 2/5 upon cooling. The noise level in volts will then be reduced by the square root of this factor, or about 63% of the room temperature value.

The estimated change in the (voltage) SNR for this coil upon cooling to 77K is then 1.58/0.63 = 2.5, slightly larger than the factor of two estimated above.

The prototype coil mentioned above was tuned and matched for testing and was sent to NRL where attempts were made to measure the changes in the SNR using the ^{14}N NQR signal from Urea Nitrate (which has NQR properties similar to those of TNT). While some improvements were observed, the results of these tests are still not fully understood.

To help reduce the thermal coupling for this test coil, the matching was done using a moving coupling coil which was outside the liquid nitrogen, and a mutual inductance coupling scheme. This scheme worked very well and in principle could be automated using a simple motor. Thus it has promise to replace the switched capacitor scheme currently used by Quantum Magnetics as a way to reduce the weight of hand-held NQR probes. Also of note is that even for the simple styrofoam container used, 1 liter of liquid nitrogen would last approximately 1 hour. Thus, the use of liquid nitrogen rather than active refrigeration (which requires over a kW of input power even for this small coil) is preferred.

Flat Birdcage-like coil array

Birdcage RF coils[1,2] have been found to be very useful, particularly for magnetic resonance imaging (MRI). Typically these are in a cylindrical geometry and have the properties that the RF magnetic field produced is very uniform and they can be driven in quadrature - for instance to provide a circularly polarized RF magnetic field (see below). Such a coil is designed to surround the sample of interest and hence has limited direct utility for the detection of explosives.

The typical birdcage coil can be thought of as an array of LC circuits arranged around the surface of a cylinder.[2,3] These LC circuits are coupled primarily by their mutual inductance.[3] To some extent, the birdcage coil can be regarded as a length of transmission line which is connected back to itself.

To examine the possibility of using a similar arrangement as a surface coil, a flat coil array as shown in **Figure 1** was constructed and examined. This arrangement can be considered to be a (high-pass) birdcage coil originally on a cylinder of length L, which has been unrolled.

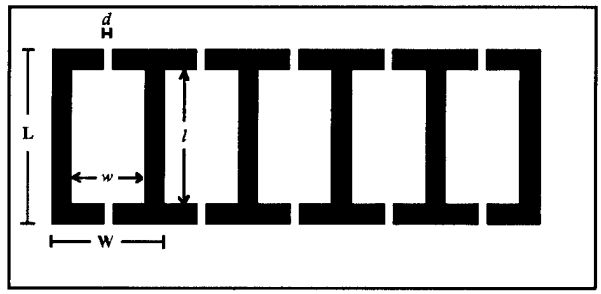

Figure 1 - Flattened birdcage coil used: L = 20.2 cm, W = 9.2 ± 0.1 cm, l = 15.2 cm, w = 4.15 ± 0.05 cm, and d = 0.3 to 0.4 cm. Capacitors are placed across the gaps.

The coil was constructed using nominal 1" wide copper tape on a plexiglass backing and all capacitors are ATC 2200 pF series E. For a single loop, the resonance was measured (using the standard 2-probe technique) to be 11.25 MHz with a Q of 237. Various subsets of coils (including both adjacent and distant pairs, various triplets, and a group of four) were examined. Detailed results for all measurements were transmitted to Garroway's group at NRL in October 1999 and are only summarized here.

The various resonant frequencies measured were consistent with what one might expect for a discrete number of coupled resonant circuits. With all five coils, five resonances were observed, with frequencies of 9.62, 10.14, 11.05, 12.58, and 14.76 MHz. While the relative phases of the RF fields near each loop could only be measured semi-quantitatively, the general conclusion is that indeed this can be viewed as a truncated piece of transmission line. The two highest frequency modes corresponding to a ½ wavelength resonance, the next two corresponding to 1 wavelength, and the lowest to 3/2 wavelengths. Numbering the normal modes from 1 to 5 with 1 being the highest frequency and 5 being the lowest, modes 1, 3, and 5 have nodes near the ends and modes 2 and 4 have a node near the middle. That is, using the center of the coil as the origin, the odd numbered modes qualitatively look like cosine functions, and the even number sine functions.

The strength of the RF fields produced as a function of distance from the coils showed that for most modes, the field drops off exponentially with distance, at least over a range of distances comparable to the size of the coil. In some cases, the field dropped off a bit faster than would a simple exponential.

The exponential fall-off of the RF magnetic field with distance may prove useful in situations where there is a desire to confine the field to a small volume. Unlike the cylindrical birdcage coil,

there is no obvious way to drive this coil in quadrature at a single frequency. It may be desirable to reexamine this type of coil for multi-frequency NQR sometime in the future (see 3-frequency NQR below). We note, however, that while the Q of the coil array measured is quite adequate (unloaded, unmatched Q's of close to 300), the Q's would be expected to be considerably less at frequencies needed for ^{14}N NQR (0.5 - 5 MHz) and this may be a problem.

SNR Calculations using Mutual Inductance

Equations were developed some time ago to estimate the expected signal-to-noise ratio (SNR) for magnetic resonance experiments. These equations invariably include a fudge factor known as the 'filling factor'. This factor is included to take into account (approximately) the fact that the RF magnetic field produced by the coil exists in a larger volume than does the sample being investigated. Such a factor is convenient and works well for typical magnetic resonance measurements. However, for surface coils, it is less clear how to compute or use such a factor.

An alternate way to visualize and compute the SNR appropriate for surface coils was developed as part of this study. It turns out that the coupling between the RF coil and the sample can be viewed as a simple mutual inductance problem. For simple geometries, it is straight-forward to compute the required mutual inductance, or alternatively one can use Grover's tables,[4] from which the SNR can be estimated without the need for a 'filling factor.'

The details of this type of calculation, as appropriate for NQR materials detection, were communicated to Garroway's group at NRL and will appear in an upcoming joint publication[5] and so will not be reproduced here.

Circular Polarization Calculations

As part of this work, extensive calculations were made to investigate the size of the NQR signal expected when a circularly polarized RF magnetic field is used. Such a field is generally produced using a coil array consisting of at least two orthogonal sets of coils fed out of phase. The potential advantages of circular polarization are that one can more effectively irradiate and measure a larger fraction of the nuclei in the sample and that many resonant acoustic ringing signals (and other similar undesirable signals) can, in principle, be separated from the desired NQR signal because they are inherently linearly polarized.

Results of initial calculations[6] were sent to Garroway's group at the NRL early in 2000 and are only summarized here. Starting from basic quantum mechanics for the ^{14}N (I=1) nucleus in a non-axial electric quadrupole field, it was found that if circular polarization is used for excitation and for a powder (or polycrystalline) sample, two orthogonal signals can be observed with each of the signals received looks like

$$\bar{S}_{x'}(t) = \pi\omega_+ \cos\omega_+ t \int_0^\pi d\theta \sin^2\theta \sin\left(\gamma B_1 \tau \sin\theta\right)$$
$$= 8\pi\omega_+ \cos\omega_+ t \left[\frac{J_1(\gamma B_1 \tau)}{3\cdot 1\cdot 1} - \frac{J_3(\gamma B_1 \tau)}{5\cdot 3\cdot 1} - \frac{J_5(\gamma B_1 \tau)}{7\cdot 5\cdot 3} - \cdots \right] \quad \textbf{(2)}$$

where the J_n are Bessel functions. In practice, only the first few terms in this expansion need to be included. Here, γ is the nuclear gyromagnetic ratio, B_1 is the strength of the applied RF magnetic field and τ is the length of time that field is applied. The equation shown above is for one of the three possible transitions (ω_+). In contrast, for the more traditional linear polarized NQR experiment, the single signal received is proportional to

$$\bar{S}_{x'}(t) = 2\pi\omega_+ \cos\omega_+ t \left[\sqrt{\frac{2\pi}{\gamma B_1 \tau}}\, J_{3/2}(\gamma B_1 \tau) \right] \quad \textbf{(3)}$$

Extensive measurements to test this idea were made at NRL by J. B. Miller. Miller was able to show that the general functional form of these equations seems valid, however the SNR for circular polarization is, under the conditions of the experiment, a bit larger than predicted when compared to the more traditional linear polarized measurement. Miller was also able to demonstrate the ability to at least identify acoustic ringing signals for isolated acoustic resonances using this technique. The reasons why the circular polarized technique gave signals which were somewhat larger than anticipated is still under investigation. Currently, assumptions made regarding the relative size of B_1 are under study.

3-frequency NQR - theory and coil array

For a nucleus with spin I = 1 (such as ^{14}N) in a non-axial electric quadrupole field (such as is found in the materials of interest here) there will be three energy levels, and transitions can be induced between any pair of levels using an RF magnetic field. Thus, there will be three NQR frequencies. These frequencies are denoted (in order in increasing frequency) ν_0, ν_-, and ν_+. See **Figure 2** . The traditional NQR measurement will use only one of the possible transitions at any given time.

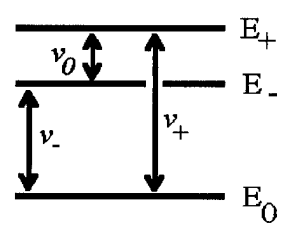

Figure 2 - Energy levels

Here we investigated the possibility of exciting the nucleus at two ofand transitions for I = 1 the possible transitions and observing the signal at the third frequency. NQR. Excitation using two of the possible frequencies has been studied for quite some time by Grechishkin's group[7,8] where signals are also observed at the same two frequencies. They refer to this as 2f NQR. During the course of that work, Grechishkin's group

noted theoretically that a signal should be observed at the third frequency, however we have been unable to find any reports of measurements made at the third frequency. We refer to NQR experiments which use all three frequencies as 3f NQR.

The potential advantage of 3f NQR for materials detection is that the received signal is now at a completely different frequency than the excitation signals. Hence, one can potentially significantly reduce the dead time following excitation, and undesirable signals which occur at the excitation frequency will not be present in the received signal. Both are important for materials detection.

The theory for the 3f signal was calculated rigorously starting with basic quantum mechanics and with the inclusion of possible RF phase shifts during the measurement. A complete report[6] was previously sent to Garroway's group at NRL and is only summarized here. There are two basic types of experiments one can employ. The two excitations can be supplied one after the other (serial excitation) or at the same time (simultaneous excitation). The theoretical computation for serial excitation is quite straight-forward. For simultaneous excitation a rather complicated set of equations is obtained, which are similar to, though somewhat more general than, those found by Grechishkin's group. What was realized during the course of the theoretical study was that the rather complicated set of equations does in fact have a relatively simple interpretation which we summarize below.

The particular case studied in detail is the case where the ν_- and ν_0 transitions are used for excitation and the signal is observed at ν_+. In order to achieve the maximum signal, the ν_- and ν_0 transitions should be excited by orthogonal RF magnetic fields and the ν_+ signal should be observed using a coil sensitive to RF magnetic fields which are perpendicular to *both* of the exciting fields. If one designates the relative sizes of the two exciting RF fields using B_{1-} and B_{10} then it turns out that the effects of that RF field are equivalent to a rotation of the nuclear spin about an axis which lies in the plane of the two exciting fields, at an angle ξ from the direction of B_{10} where $\tan\xi = B_{1-}/B_{10}$. The rotation due to a simultaneous RF pulse of length τ is through an angle $\theta = \gamma\tau(B_{1-}^2 + B_{10}^2)^{1/2}$, where γ and τ are as defined above. This simple physical interpretation of the effects of the simultaneous RF pulse seems to be new and leads to the development of more convenient operator techniques for describing the evolution of the signal, for example, for multiple pulse techniques.

Predictions for the size of the 3f NQR signal for both a single excitation (at the two frequencies) and for a simple two-pulse echo technique (two excitations each, separated by a delay) were made using numerical powder averages. Conditions to obtain the optimum signal in each case were also derived. The predicted maximum signal expected is comparable to, though somewhat smaller than, what one would obtain from a traditional single frequency NQR measurement.

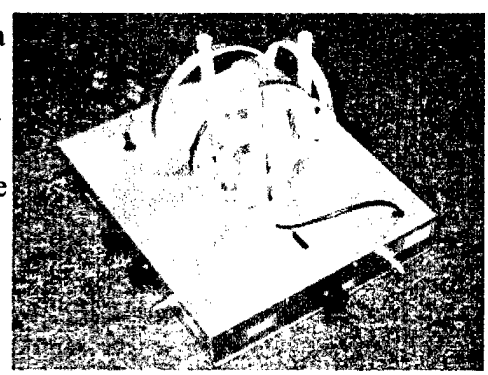

Figure 3 - Prototype coil for 3f measurements of sodium nitrite shown with rf shielding removed.

In order to expedite the experimental test of these predictions, a prototype coil array was constructed at MTU consisting of three mutually orthogonal Helmholtz coils with provisions for tuning and matching at the three

frequencies of sodium nitrite. See **Figure 3** . This coil was shipped to NRL during the summer 2000 and, after slight modification, is currently being used by K. Sauer of Garroway's group.

The predicted 3f signals are in fact observable and behave very similarly to what was predicted theoretically. Some small discrepancies between the theory and experiment are currently being examined. The extent to which the dead time can be reduced and acoustic ringing artifacts removed is still to be determined.

"No Return" coil arrays

The typical magnetic resonance signal is detected using a coil and Faraday's law of induction. The coils used can surround the sample (a "volume coil") or simply be near the sample (a "surface coil"). In both cases the coil is a physically closed loop. Here we examine the possibility of using "coils" which may be more amenable to other inspection geometries where a physically closed loop is inconvenient or at least is a less than optimal geometry. We refer to these coils as "No return" coils.

The basic idea is to employ receiving antennas similar to what are used for short wave mobile radio communications. A single such antenna is optimized for reception of distant radio sources and is primarily an electric dipole. What is desired for magnetic resonance is an antenna which is optimized for near-field magnetic field detection. An array of such antennas, connected with appropriate phases, can be made a very poor receiver for distant sources. The goal here is to do this, and at the same time make the array sensitive to near-field magnetic sources.

Figure 4 illustrates such a coil constructed from two typical short-wave receiving antennas wired as a shortened half-wave dipole, but with the dipole elements in the same direction. The current distribution shown will result in a magnetic field perpendicular to the page. By reciprocity, when used as a receiving antenna, this array will be sensitive to these magnetic fields. Initial prototypes show that this idea works in principle, however the optimum sensitivity is still too low for practical materials detection. The problem to solve is to reduce the losses in the antenna array to an acceptable level. This work has just begun and is expected to continue.

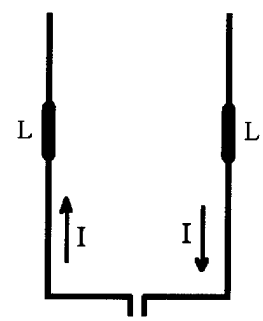

Figure 4 - Simple two-element No Return Coil.

Invention Disclosures

1. "Improved mutual inductance-based automatic impedance matching apparatus for magnetic resonance surface coils for use in the field to detect contraband substances," B. H. Suits Submitted to MTU I.P. office, Jan 2000, with copy to A. N. Garroway.

2. "Three-Frequency Nuclear Quadrupole Resonance (NQR)," Sauer, Suits, Miller, Garroway, submitted to NRL I.P. office, Dec. 2000, with copy to MTU I.P. Office.

3. "Nuclear Quadrupole Resonance (NQR) Antenna without a Current Return," Suits, Garroway, Miller, Klug, submitted to NRL I.P. Office, January 2001, with copy to MTU I.P. Office.

Publications (Directly Related to this Grant):

"Nuclear Quadrupole Resonance (NQR) for Detection of Explosives and Landmines", A. N. Garroway, M. L. Buess, J. B. Miller, K. J. McGrath, J. P. Yesinowski, B. H. Suits, and G. R. Miller, Proceedings of 6th International Symposium on Analysis and Detection of Explosives, Prague, Cz, July 1998, chap. 19, Petr Mostak, ed., Research Institute of Industrial Chemistry, Pardubice-Semtin, 1999.

"Interplay among Recovery Time, Signal, and Noise: Series- and Parallel-tuned circuits are not always the same," J. B. Miller, B. H. Suits, A. N. Garroway, and M. A. Hepp, Concepts in Magnetic Resonance **12**, 125 (2000).

"Circularly Polarized RF Magnetic Fields for Spin-1 NQR," J. B. Miller, B. H. Suits, and A. N. Garroway, Journal of Magnetic Resonance, (*submitted*).

"Remote Sensing by Nuclear Quadrupole Resonance (NQR)," A. N. Garroway, M. L. Buess, J. B. Miller, B. H. Suits, A. D. Hibbs, G. A. Barrall, R. Matthews, and L. J. Burnett, IEEE Transactions on Geoscience and Remote Sensing *(accepted and in press, Scheduled for 2001)*.

"Three-Frequency NQR," K. L. Sauer, B. H. Suits, J. B. Miller and A. N. Garroway, *(in preparation)*.

Related Presentations (by Suits):

"Some Aspects of Coil Design for NQR Land Mine Detection," Invited presentation for the International Meeting on the Advances in NQR Detection of Land Mines and Explosives (NQR-DLME), June 2000, Ljubljana, Slovenia.

"Super-Q Detection of Transient Magnetic Resonance Signals," Invited presentation for the Eigth Annual Little Rock Workshop on Advances in NMR Engineering, Penn State University, June 1999.

"NQR Detection of Explosives: Fighting Terrorism with the Harmonic Oscillator," MTU Physics Dept Colloquium, Houghton, MI, April 1999.

"NQR: What's the same and what's different?" Invited plenary talk, 5th International Conference on Magnetic Resonance Microscopy (ICMRM), Heidelburg, Germany, Sept 1999.

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5. "Remote Sensing by Nuclear Quadrupole Resonance (NQR)," A. N. Garroway, M. L. Buess, J. B. Miller, B. H. Suits, A. D. Hibbs, G. A. Barrall, R. Matthews, and L. J. Burnett, IEEE Transactions on Geoscience and Remote Sensing *(accepted and in press, Scheduled for 2001)*.

6. "Some calculations for NQR of spin-1 Nuclei in powders," B. H. Suits, unpublished report, February 2000.

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